Deep sub-barrier fusion reactions of the light nuclei ^{12}C and ^{16}O

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Fusion reactions relevant for the carbon and oxygen burning cycles in highly evolved stars are investigated in a standard approach to fusion. We employ the double folding method to evaluate the ion-ion interactions with Gogny-D1 and M3Y-Paris $n-n$ effective forces. The cross-section evaluation do not indicate a possible hindrance even at the lowest energies under the barrier. Reaction rates at temperatures relevant for the stellar processes are estimated and compared to the traditional and modern extrapolation formulas.

The experimental data on sub-barrier fusion, accumulated in last years, disclosed a new phenomenon, which consists in a severe reduction of the cross sections once the bombarding energy is approaching a threshold value [1]. Until recently the application of the standard coupled channel model failed in resolving the cross-section hindrance puzzle. Starting with 2005 we performed a systematic investigation of the various fusion reactions exhibiting this phenomenon at low bombarding energies. The fundamental ingredient in our approach was the nucleus-nucleus potential, which differs from the traditional one, such as the Woods-Saxon or Akyüz-Winther, by an additional term dictated by the necessity that nuclear matter saturates. The result of this modification is a massive change of the nucleus-nucleus potential inside the Coulomb barrier. From quantum-mechanical point of view we simply deal with a decrease of the transmission probability across the barrier and consequently a hindrance in fusion. We succeeded in obtaining a very good description of the fusion cross-sections for medium-heavy projectile target combinations [2,3], medium-heavy projectile and medium-light target [4], medium-light projectile and target [5], light projectile and heavy target [6]. Typical to all the reactions displaying fusion hindrance at energies deep under the barrier is also the fact that the S-factor has an apparent maximum near the threshold energy.

Since the hindrance phenomenon occurs over a wide range of heavy-ion masses, it is then of interest to search also for other projectile-target combinations that might display the same hindrance features. Very recently, it was conjectured by Jiang et collab. that the hindrance could also affect the stellar reactions rates [7]

Although the heavy-ion literature is abundant in studies on the sub-barrier reactions involving ^{12}C and ^{16}O we reinvestigate in this work their fusion cross-sections using the double-folding heavy-ion potentials derived from finite-range effective $n-n$ forces, with or
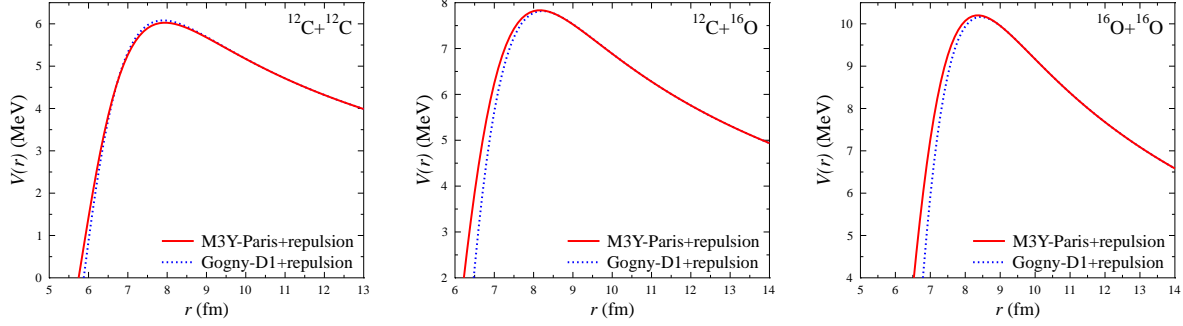
Figure 1. Ion-ion potentials for the three reactions investigated in this work. Solid curve is the potential based on the M3Y-Paris $n-n$ effective interaction whereas the dotted line was obtained with the Gogny-D1.

without density-dependent contributions. We provide a more accurate local equivalent of the non-local exchange potential by using the Perrey-Saxon procedure and the densities of the reacting nuclei were derived from a spherical Hartree-Fock calculation using the density functional of Beiner and Lombard [8]. The strength of the surface term in this functional was slightly adjusted in order to reproduce exactly the experimental binding energy [9]. In this approximation, the experimental charge r.m.s radii (compilation of Angeli [10]) are reproduced to better than 0.5%. We plotted in Fig.1 the potentials for the three reactions under investigation ($^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$). Both forces produce the same barrier height and small differences can be observed in the barrier's thickness at very low energies.
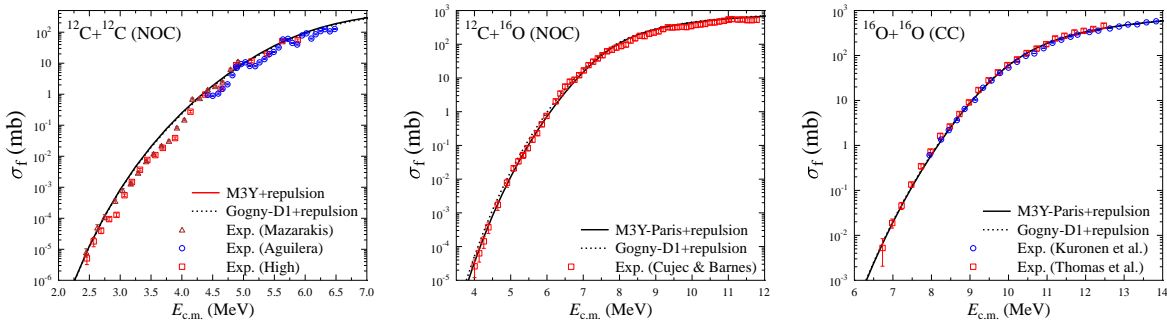

Figure 2. Fusion cross-sections corresponding to the combinations and interactions given in Fig.1

The corresponding fusion cross-sections, calculated using the incoming-wave boundary condition, are displayed and compared to experimental data in Fig.2. The first two reactions are well reproduced in the no-coupling (NOC) approximation, whereas the re-

action ^{16}O+^{16}O necessitates the application of the coupled-channel method. Apart of the ^{12}C+^{12}C cross section which exhibit resonant structures under the barrier the data are nicely described. On the other hand we could not find any maximum in the S-factor, which tells us that for such light ions the hindrance apparently plays no role.
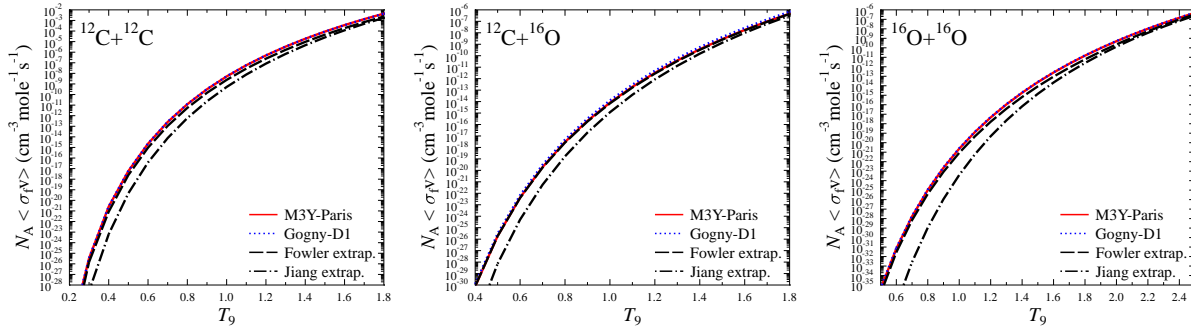

Figure 3. Reaction rates for the three astrophysical reactions. The results obtained with the two potentials used in this paper are compared to the extrapolations of Jiang [7] and Fowler [11]

In order to asses the effect of the calculated cross sections at energies relevant for stellar burning cycles we calculated and present in Fig.3 the reaction rates for the three astrophysical reactions. The fact that our predictions are close to the Fowler reaction rate should not be surprising since no hindrance effect is incorporated in that extrapolation. The predicted reaction rate is in all cases only weakly dependent on the type of finite-range force employed in the calculation of the double-folding potential. On the other hand in the early phases of the hydrostatic burning stage the predicted curve and the Fowler extrapolation are pointing to a speed-up of the carbon and oxygen burning compared to the extrapolation formula based on hindrance.

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